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# Integrated power control for small wind power system

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## HIGHLIGHTS

► We establish the transition diagram of energy flows under various working modes for small wind power system.
► We present a method of integrated power control for small wind power system to achieve its optimal and reliable operation.
► We develop an optimization management strategy for lead acid battery in small wind power system.
► We design an intelligent power controller with the function of energy optimization management.

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## ABSTRACT

A small wind power system (SWPS), which comprises a buck-type DC/DC converter and a microcomputer control unit, is presented for improving its reliability and energy conversion efficiency. The relationship between energy flows for the suggested SWPS is analyzed, and the transition diagram of energy flows under various working modes is established. An integrated power control method is put forward that contains maximum power point tracking, load power tracking control, over speed protection, and optimization of battery management. A power controller which is based on the integrated power control strategy is designed, and its performance is tested on the experimental platform for SWPS. Experimental results indicate that the controller can switch on automatically working modes to maintain the energy balance of the proposed SWPS under the conditions of variable wind speeds or loads. Moreover, the wind turbine can utilize wind energy efficiently at the premise of secure operation, and the battery life can be prolonged on condition of reasonable energy management. Therefore, the suggested integrated power control method in this paper can make the SWPS to obtain optimal and reliable operation.


## 1. Introduction

Wind energy is one of the most important renewable energies and it is drawing more and more widespread concern because of its advantages of being free from pollution and being inexhaustible. Small wind power system (SWPS) is suitable for those areas where wind resource is abundant and conventional electricity is difficult to reach due to technical and economical restraints. SWPS will play an active role in both improving the energy supply structure and promoting the environmental construction, and it has widespread market prospects [1–4]. Although SWPS has been widely used, various barriers such as policy and technology affect its application and development [5–7]. At present, the energy conversion efficiency of the conventional SWPS is relatively low [8–12]. Moreover, some wind turbines often fall into vibration or over speed due to the delay and failure of the mechanical braking device [13–16]. In addition, lead acid batteries are typically used in SWPS due to their maturity sturdiness, stability and low cost. However, unfavorable working conditions make the lifetime of lead acid batteries shorter than one might expect [17–20]. Therefore, effective power control for SWPS can ensure the continuity and stability of power supply.

In order to improve efficiency and obtain optimal operation for SWPS, a simple and economic SWPS is proposed in this paper. The relationship between energy flows is also analyzed. An integrated power control method is established for the SWPS to achieve energy balance and secure operation. A rational energy management scheme for lead acid batteries is proposed. A power controller with the function of energy optimization management is designed. Experiment studies, based on the test platform for SWPS, are carried out to verify the correctness and feasibility of the proposed integrated power control method.

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## 2. Proposed system description

SWPS is mainly used in remote areas where the environment is relatively poor, so the structure for the system must be stable and reliable besides the system's lower installation cost and higher operation efficiency. Fig. 1 shows a simple and economic SWPS, which consists of a fixed pitch wind turbine, a permanent magnet synchronous generator (PMSG), a lead acid battery bank, a power converter, an inverter, a dump load and a controller. The wind turbine directly drives the PMSG, and the controller regulates the power converter in variable modes according to different external conditions. The bank of battery is used in parallel with the inverter to reduce the voltage variations of the DC bus. The battery delivers the energy difference between the load demand and the energy from the wind turbine to achieve the energy balance of the system. If the wind turbine generates more energy than required by the load, the excess energy is fed to the battery. The controller directly adjusts the duty of the DC/DC converter for energy management. The rotational speed of the wind turbine is measured by the way of the relationship between the frequency of AC voltage and the rotation speed of the generator, so there are no mechanical sensors like wind velocity and rotation speed sensors in this system. The protection of over speed for the wind turbine is performed by the dump load. The inverter converts DC power into AC power with rated magnitude and frequency to supply the load.

## 3. Energy optimization management

The SWPS can be grouped into different parts such as the wind turbine unit, the energy storage unit and the load unit. The wind turbine unit can run at the states of maximum power point tracking (MPPT), load power tracking control (LPTC) or over speed protection (OVP) according to the changes of wind speed or load. If a larger load comes into the system under rated wind speed, the wind turbine runs at the MPPT state to capture efficient wind energy. Otherwise, the wind turbine runs at the LPTC state to balance energy while a little load is connected with the system. When wind speed exceeds the rated value, the wind turbine runs at the OVP state to achieve secure operation. The energy storage unit shows the nature of load in charging state or the performance of power source in discharge state. In order to obtain reliable operation, the power output of the wind turbine should balance the sum requirement of the loads and the energy storage unit. Therefore, the SWPS has mainly 8 kinds of operation modes according to the power relationships between the wind turbine unit, the load unit and the energy storage unit. These operation modes switch automatically with each other according to variable weather or load, and the working status of each unit can be determined by the corresponding voltage and the current. The transition diagram of various working modes is shown in Fig. 2.

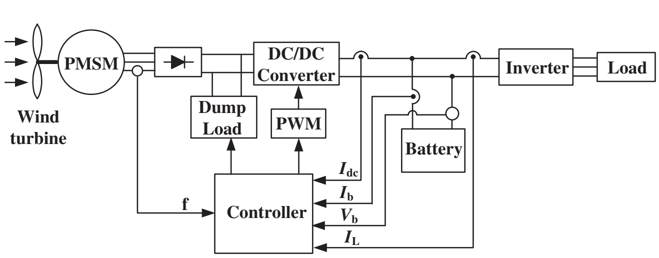


**Fig. 1.** Proposed system structure.

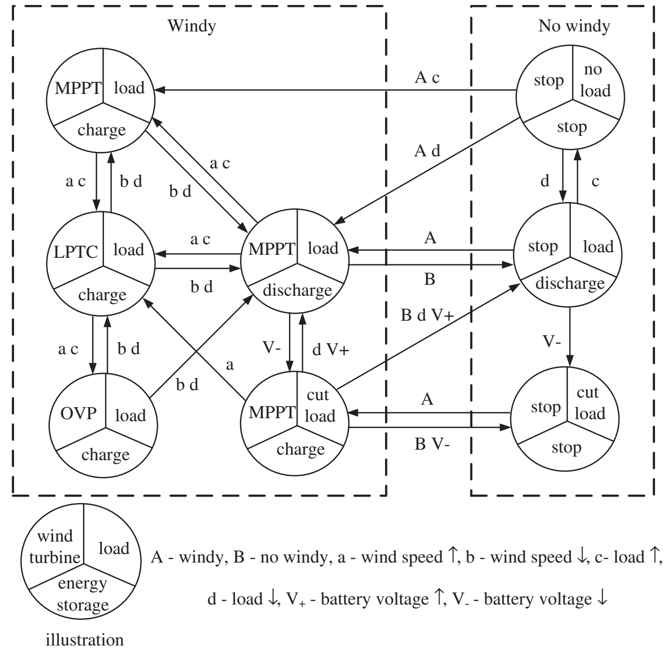


**Fig. 2.** Transition diagram of working modes for SWPS.

## 4. Wind turbine control

### 4.1. Maximum power point tracking (MPPT)

In order to extract effectively wind energy, the wind turbine should operate at MPPT state under rated wind speed. In this paper, a variable step size adaptive hill climbing method is used to achieve MPPT. The voltage of the DC bus is almost constant in a short time because of the clamping action of the battery, so the regulation for the current output of the converter is approximately the adjustment of the power output. The control method starts to choose initial reference duty $d_0$ and measures the corresponding current output, then a small disturbance value adds to $d_0$ and the variation of power output is detected. The power variation decides next step disturbance direction. If the power does not reach the maximum power point, the disturbance value increases or decreases by one step. If the disturbance leads to the power increasing, the regulation is done in the same direction or opposite direction. This process is repeated until the maximum power point is reached.

Disturbance magnitude is a critical parameter for hill climbing method. If the disturbance magnitude is too big, large fluctuation will occur on both sides of the maximum power point. If the disturbance magnitude is too small, it will be not easy to detect the current difference at sample times, and not beneficial to get the better performance of rapid control. Here, the disturbance magnitude is selected according to the change rate of the current output. When the error of the current output changes violently, a larger disturbance step is employed. When the current output is within error, the disturbance is stopped to avoid the phenomenon of the power turbulence near the maximum power point. The duty $d$ of the DC/DC converter is adjusted according to following equation.

$$d(kT) = d(kT-1) + \alpha \times \Delta I \tag{1}$$

where $T$ is the sample period, $\Delta I$ is the change of the current output, and coefficient $\alpha$ is determined according to equation (2).

$$\alpha = \begin{cases} 1, & |\Delta I| > \Delta I_m \\ 0.5, & \varepsilon < |\Delta I| \le \Delta I_m \\ 0, & |\Delta I| \le \varepsilon \end{cases} \quad (2)$$

where $\Delta I_m$ and $\varepsilon$ are respectively the maximum error and the minimum error of the current change.

### 4.2. Load power tracking control (LPTC)

The generated energy by the wind turbine should match the load demands in the SWPS. When the captured energy is greater than the consumption of the loads and the acceptable energy of the battery, the wind turbine undergoes over power, which causes the increase of the wind turbine speed and may be engender the consequences of harming its safe operation. Therefore, the controller regulates the wind turbine to run at LPTC state for energy balance when over power is detected. The controller adjusts the generator speed and makes the tip speed ratio of the wind turbine to deviate from the optimal value, so the absorption of wind energy is reduced to match the demand of the load and the battery. As a result, the power balance is obtained.

In order to realize LPTC, the power requirement from the load and the battery is summed up to work as the given control amount of the DC/DC converter. As the voltage of the DC bus is almost constant with the clamping action of the battery, the regulation of the current equates the adjustment of the power. The load current $I_L$ is dynamic changes with the load change, and the battery charging current $I_B$ adjusts according to the state of charge (SOC) of the battery. The real time load current adds the allowable maximum charge current of the battery, then the sum is acted as a setting value of the current output of the DC/DC converter, and both PI regulator and pulse width modulation (PWM) are applied to regulate the duty of the DC/DC converter for transforming impedance. Thus, the generator power output always matches the load power and the charging power of the battery. The LPTC structure which implements the above mentioned control strategy is sketched in Fig. 3.

### 4.3. Over speed protection (OVP)

Considering the limitations of mechanical strength on rotating components of the wind turbine and power restriction on the generator circuit, the wind turbine speed should be controlled within a reasonable range. The dump load is employed to prevent the wind turbine from over speed in this SWPS. The braking principle with the dump resistance can be drawn from Fig. 4. The link line of the maximum power point at different wind speed is defined as power peak line here. Assuming the dump resistance is $R_4$ and the SWPS runs at point A when wind speed is $V_3$. If the dump resistance decreases continuously from $R_4$ to $R_2$, the operating route of the wind turbine rises from point A to point B, then it goes down to point C. It can be seen that the wind turbine speed decreases gradually, and the aim to limit the speed seems to be achieved. However, the wind turbine power has a tendency from increase to decrease, and the generator current may exceed seriously the permitting value. In addition, if the wind speed continues increasing at this time, the generator will stay at over power state for a period. In other cases, if the initial match locates at point C which is in the left region of the power peak line, the wind turbine runs from point C to point D when the dump resistance reduces to $R_1$. As a result, both the power and the speed of the generator are reduced rapidly. Therefore, when the match relationship between the wind turbine and the generator locates in the left region of the power peak line, it is more reliable for the dump resistance to prevent the wind turbine from over speed.

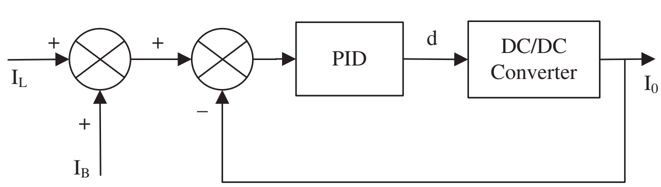

**Fig. 3.** Structure for load power tracking control.

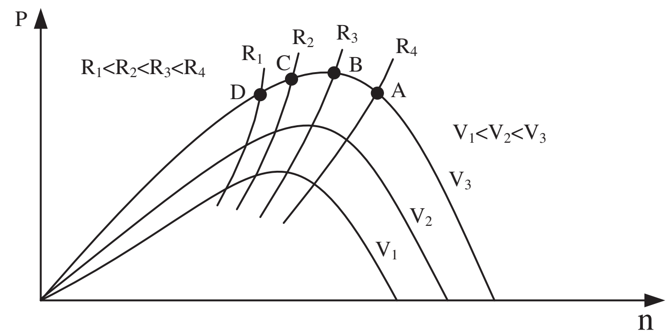

**Fig. 4.** Match between the wind turbine and the generator.

In general, the DC/DC converter adjusts the generator's speed in a reasonable range under the rated wind speed. When the generator's speed is beyond the adjustable range of the DC/DC converter, the dump load drags the wind turbine into the stall area to avoid over speed.

## 5. Battery optimization management

### 5.1. Charging control

The discharge amount of the battery is frequently greater than the charging amount at low wind speed. If the battery stays at incomplete charging for long time, sulphation will take place and it shortens the battery's lifetime. On the other hand, the charging curve of lead acid battery indicates that the increase of charging current can improve the charging rate and restore the battery capacity quickly. It can be drawn from the charging curve that the battery voltage gradually moves upward in the charging process. When the terminal voltage of the battery reaches a certain value, polarization will occur and it obstructs the acceptable charging rate of the battery. However, the capacity of the battery is only restored about 60% at this moment. If the charging current is decreased immediately, polarization phenomenon can be eliminated automatically. Many researches indicate that larger charging current with intermittent depolarization pulse can eliminate the concentration gradient or polarization in the battery. However, it is found that the SWPS can only produce a little energy at low wind speed, and the charging current is less than the maximum acceptable current of the battery. The captured wind energy cannot let go in vain, so the control way of large charging current with intermittent pulse discharge is not feasible for the lead acid battery in the SWPS.

This paper presents a fast charging control strategy to restore the capacity of the battery as quickly as possible, and this way uses different charging rates at different phases. If discharge is detected at any time and the generator can offer surplus energy, the battery is charged immediately. If the wind turbine can provide enough energy, the maximum permitting current, which is equal to the maximum acceptable charging current, is used to accelerate the charging process. The charging current cannot exceed the

maximum permitting charging current during the whole charging process, and the maximum permitting current decreases gradually with the restoration of the battery. Because the change of the battery terminal voltage $U_B$ reflects the polarization degree which has relations with the acceptable rate of the charging current, the battery voltage is detected in real time and the maximum acceptable charging current is also adjusted dynamically according to the battery voltage. If the battery voltage reaches the setting value $U_{set}$, it indicates that the charging current is more than the acceptability of the battery and overcharge reaction will happen, so a lower charging current is used to eliminate the overcharge reaction. This process is repeated until the charging current reaches to $C/100$, where $C$ is the capacity of the battery in A h. It indicates that the battery capacity has been restored to 100%, then a trickle charging current is used to supplement the self-discharge losses of the battery. Ambient temperature has a significant influence on the battery terminal voltage, so the setting value to adjust the maximum allowable charging current is compensated with the different environment temperature. The coefficient of compensation is $-3.5$ mV $^{\circ}C^{-1}$ for each cell in this paper. Fast charging process with variable currents is shown in Fig. 5.

### 5.2. Discharge control

Unreasonable discharge control also causes the premature failure or capacity loss of the lead acid battery. Under the same forbidden discharge voltage, a different discharge current leads to the battery to reach different discharge. If a larger discharge current is used, it drops the battery voltage more quickly and the battery can only release less energy. On the contrary, a smaller discharge current can make the battery emit more energy, but the battery lifetime will be shortened at deeper discharge.

This paper proposes a way of discharge control that combines hysteresis voltage with current compensation. If the wind turbine cannot offer enough energy for the load, the battery is discharged to supply energy for the load. The voltage of the battery goes down along with the discharges process. When the battery voltage is below the forbidden discharge value $U_{fd}$, the load is cut off to avoid excessive discharge. Then the battery must be charged to restore the lost energy. The battery voltage increases following the charging process, and the voltage only rises above the permitting discharge value $U_{pd}$, then the discharge process is allowed again. The control process is shown in Fig. 6.

In order to ensure that the battery can release the same amount of energy at various discharge currents, $U_{fd}$ is regulated timely according to the dynamic variation of the discharge current. Namely, $U_{fd}$ is set to a lower value at a larger discharge current or a higher value at a lower discharge current. The compensation relationship between $U_{fd}$ and the discharge current $I_B$ is shown in Fig. 7.

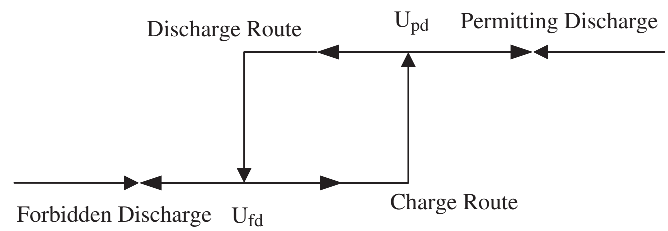


**Fig. 6.** Discharge control with hysteresis voltage.

## 6. Controller design

### 6.1. Power electronics interface

The PMSG directly connects with the three phase diode bridge rectifier in the proposed SWPS. Ignoring the internal resistance of the PMSG and considering the commutation voltage drop of the rectifier, the circuit vector diagram for the PMSG with the rectifier under '$d$–$q$' reference frame is shown in Fig. 8.

The $q$ axis current $i_q$ can be expressed as

$$i_q = \frac{V_{dc}}{\omega L_S}\sqrt{1-\left(\frac{V_{dc}}{K_V\omega}\right)^2} \tag{3}$$

where $L_S$ is the armature winding inductance, $V_{dc}$ is the output voltage of the rectifier, $K_V$ is the voltage constant, and $\omega$ is the angular speed of the PMSG.

Thinking of the salient pole of the PMSG, the electromagnetic torque $T_e$ for the PMSG can be expressed as

$$T_e = \frac{3}{2}p\frac{V_{dc}\phi}{\omega L_S}\sqrt{1-\left(\frac{V_{dc}}{K_V\omega}\right)^2} \tag{4}$$

where $p$ is the pole pairs number, $\phi$ is the rotor flux.

If $V_{dc}$ is given a constant value, the generator has a corresponding minimum rotational speed $\omega_{min}$, which can be expressed as

$$\omega_{min} = V_{dc}/K_V \tag{5}$$

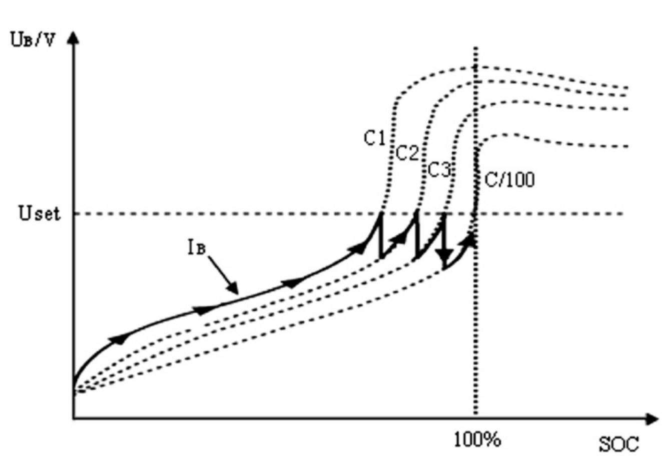


**Fig. 5.** Fast charging process with variable currents.

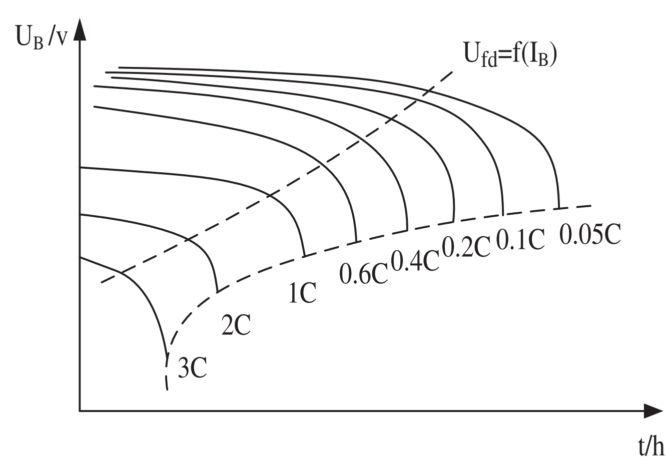


**Fig. 7.** Hysteresis voltage adjustment with current compensation.

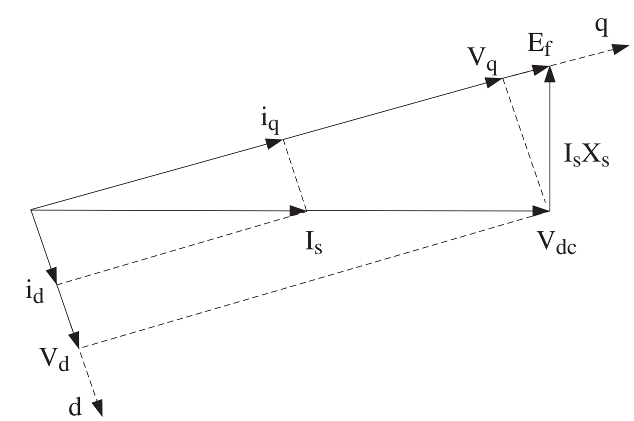


**Fig. 8.** Circuit vector diagram for PMSG with rectifier.

Torque relationship between the wind turbine and the generator is shown in Fig. 9. It can be seen that $V_{dc}$ influences the wind turbine's operation. When the speed of the wind turbine is lower than the minimum rotational speed, the generator cannot produce power. In a typical SWPS, the generator's speed almost keeps constant as the battery voltage cannot mutate in short time, so the wind turbine runs at a constant speed. As a result, the tip speed ratio often deviates from the optimum value, and the efficiency to capture wind energy is low. Therefore, a DC/DC converter should be inserted between the diode bridge rectifier and the battery to change the wind turbine's speed for maximum power point tracking control.

If the designed voltage of the battery is higher than the rated voltage output of the rectifier, a boost converter should be selected to draw down the rectifier output to match the minimum rotational speed of the generator. On the contrary, if the voltage of the battery is low, a buck converter should be inserted between the battery and the rectifier. The buck converter can lift up the rectifier's output, but the chosen lower voltage of the battery can pull down the rectifier's input to meet the requirement of the minimum rotational speed at a low speed. In addition, the capacity of the energy storage may be increased by expanding the battery group in parallel. It can be seen that the lower designed voltage output of the rectifier makes the lower minimum rotational speed of the generator. However, wind energy is proportional to the wind speed cube, so it is not practically significant to capture energy at a very low wind speed.

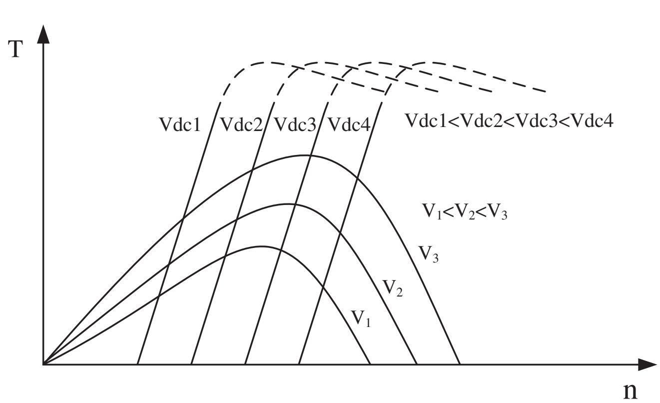


**Fig. 9.** Torque of wind turbine and generator.

### 6.2. Controller synthesis

A 1 kW power controller which is based on the method of integrated power control is designed. A buck converter is employed as the main circuit structure and a microcomputer is used as the control unit. The DC voltage of 24 V is used as the rated working voltage of the DC bus, which is equal to the voltage of the battery in the proposed SPWS. Because the designed voltage of the bus is low, the buck converter can meet the requirement of the generator's output at a low wind speed. A filter network is also used to eliminate the pulsating input current of the buck converter. The microcontroller adjusts rationally the operation of each working unit to achieve high-efficient and reliable operation by means of the detected corresponding signal.

In order to verify the correctness and feasibility of the integrated power control method for the suggested SWPS, the performance of the designed controller is tested on the experimental platform for the SPWS in laboratory. The experimental platform is mainly composed of a 1 kW PMSG, a 24 V VRLA battery group, a single phase sine wave inverter and an incandescent lamp box that can be switched back and forth to change the load magnitude.

## 7. Experiment results

It can be seen from the relationship between energy flows that the controller switches among the working modes of the SWPS according to variable weather and load, so a lot of state transition relationships can be deduced. However, there is regularity among these working situations. Therefore, some representative working processes are carried out as follows.

### 7.1. Case 1: MPPT process

When captured wind energy is less than the total demand from the load and the battery, the wind turbine works at the MPPT state. The experimental result for MPPT is shown in Fig. 10. It can be seen that the generator's output is consistent with the variable trend of the wind speed in the entire experimental process. The generator produces more power when wind speed increases after 30 s, and the contrary situation also takes place at 70 s. A large load is connected with the system at 20 s, but the generator's output does not change in this process, which indicates that the wind turbine runs at the MPPT state. Because a large load comes into the system at 20 s and the wind turbine cannot offer enough energy, so that the battery releases energy to achieve the power balance of the system,

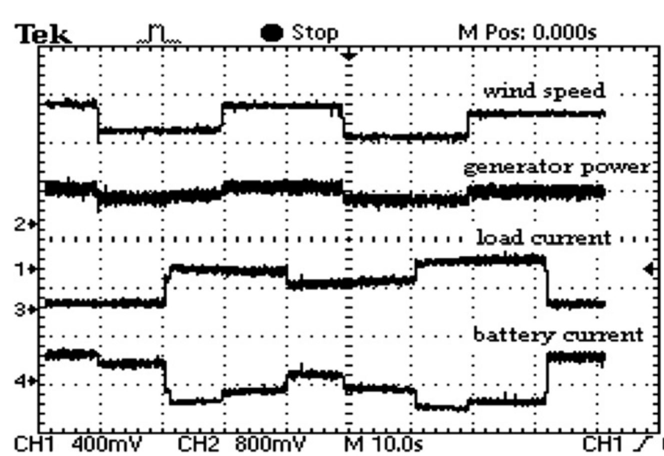


**Fig. 10.** MPPT at variable wind speed and load.

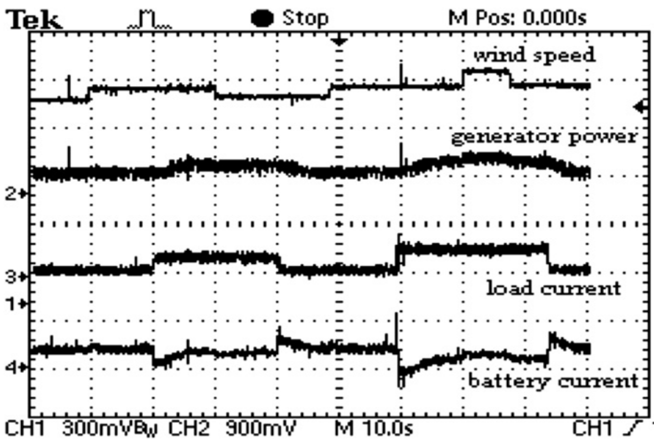


**Fig. 11.** LPTC at variable wind speed and load.

and the current of the battery transfers automatically from positive to negative, which indicates the battery is releasing energy for the load.

### 7.2. Case 2: LPTC process

When the generator produces more power than the requirement of the load and the battery, over power will take place and the controller adjusts the wind turbine to run at the LPTC state to maintain energy balance. Fig. 11 is the experimental results of the LPTC state. It is shown that the generator output has the same trend with the load variation, but the variable wind speeds cannot influence the generator's output. It indicates that the controller adjusts the generator's output to meet the dynamic requirements of the load and the battery during the variety of wind speeds and loads.

### 7.3. Case 3: mode controlled switching between MPPT and LPTC

The SWPS switches on operating states according to different wind speed or load, the experimental result for the switching state between MPPT and LPTC is shown in Fig. 12. The generator power increases and the battery current changes from positive to negative, when a load is suddenly connected with the system after 10 s. It is indicated that the generator power cannot meet the demand of the load, and the controller adjusts the wind turbine to work at the MPPT state. In the mean time, the battery supplies energy to keep the power balance of the system. The generator's power changes in accordance with the variable trend of wind speed until 50 s, and the large load is removed from the system at that time. As a result, the generator power exceeds the demand of the loads and the battery, so the wind turbine goes back the LPTC state and the battery current also returns positive for being recharged. Then the wind turbine works at the LPTC state after 50 s, and the generator power is consistent with the variable trends of the loads. It is shown that a load links with the system in 70 s, the battery instantaneously releases power to supply insufficient energy that is caused by the delay reaction of the wind turbine. The battery returns to the charging state again after the interim process. In a word, the experimental result displays that the controller can automatically adjust energy flows to maintain power balance.

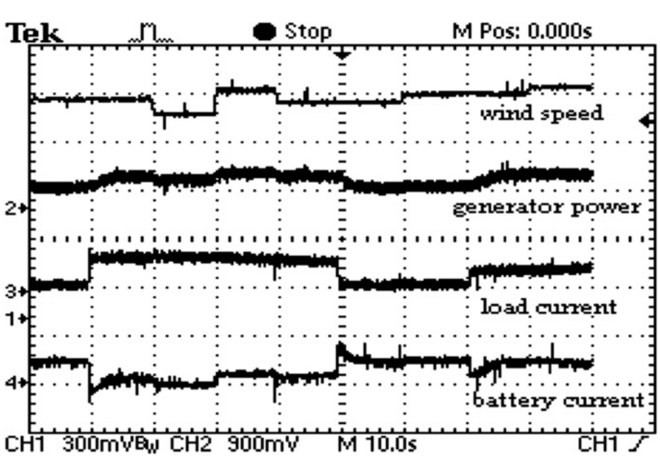


**Fig. 12.** Transaction between MPPT and LPTC.

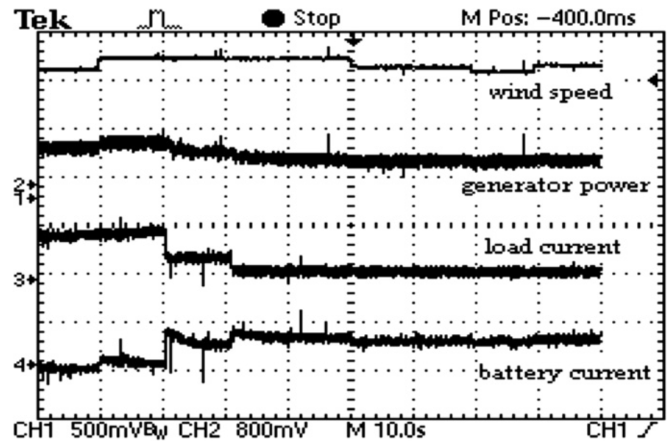


**Fig. 13.** Transient process of fast charging with variable current.

### 7.4. Case 4: fast charging the battery with variable current

The transient process for fast charging with variable currents is shown in Fig. 13. The battery releases energy to supply the loads requirement at the initial stage. It can be seen that the load current reduces progressively and the battery current also transfers from negative to positive gradually after 20 s, and the battery stays at the charging state. Because the generator's output exceeds the requirement of the loads and the battery after 30 s, the controller regulates the generator to work at the LPTC state. It is shown that the charging current is limited in the range of maximum acceptability through the whole LPTC state, and the charging current keeps a constant value after 30 s. Therefore, overcharge can be prevented.

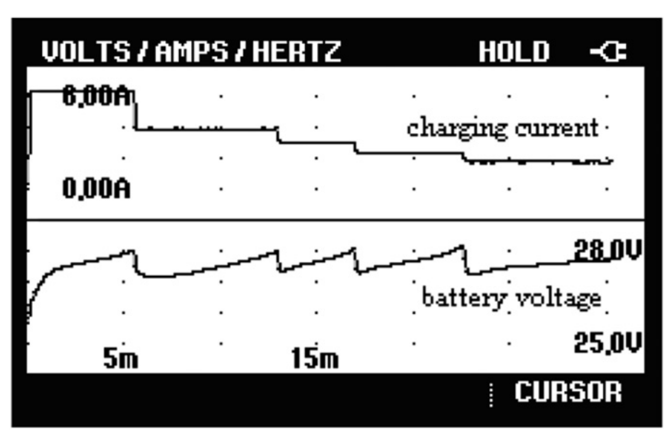


**Fig. 14.** Fast charging process with variable current.

Because the length of above recorded waveform with digital storage oscilloscope can only reflect finite charging process, so a power quality analyzer FLUKE 43-B is used to record the complete charging process in Fig. 14. It takes a long time for the battery to recover its complete capacity if its initial storage is low. Thus, following studies are carried out in the case that the battery has stored some energy. The detected battery voltage in real time is compared with the setting value, and the charging current is adjusted timely on the basis of the comparison results. It is shown that the controller reduces the charging current when the battery terminal voltage reaches the setting point in 5 min. As a result, the battery voltage reduces automatically, and polarization is eliminated. Then a lower current is used to charge the battery in the next cycle.

## 8. Conclusion

SWPS is an effective way for remote areas to obtain clean and efficient electricity, so it has a good application prospect. This paper has presented an SWPS which comprises a high-efficiency buck-type DC/DC converter and a microcomputer control unit. An integrated power control method is put forward that contains maximum power point tracking, load power tracking control, over speed protection, and the optimization management of the battery. Experimental results of the proposed SWPS indicate that the controller can switch automatically on working modes according to variable wind speed or load. Moreover, wind energy can be extracted efficiently at the premise of secure operation of the system, and the battery life can be prolonged on condition of reasonable energy management. Therefore, the suggested integrated power control method can make the SWPS to obtain optimal and reliable operation.

## Acknowledgements

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## Glossary

*Abbreviations*
*SWPS:* small wind power system
*PMSG:* permanent magnet synchronous generator
*MPPT:* maximum power point tracking
*LPTC:* load power tracking control
*OVP:* over speed protection
*PWM:* pulse width modulation

*Generator parameters*
$i_q$: $q$ axis current
$L_S$: armature winding inductance
$\omega$: angular speed
$p$: number of pole pairs
$\Phi$: rotor flux
$\omega_{min}$: minimum rotational speed
$K_V$: voltage constant
$T_e$: electromagnetic torque
$V_{dc}$: rectifier voltage output

*Battery parameters*
$U_B$: battery voltage
$I_B$: battery current
$U_{fd}$: forbidden discharge voltage
$U_{pd}$: permitting discharge voltage
*SOC:* state of charge